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On the Chemical Composition of L-Chondrites

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Abstract. Radiochemical neutron activation analysis of Ag, As, Au, Bi, Co, Cs, Ga, In, Rb, Sb, Te, Tl and Zn and major element data in 14 L4-6 and 3 LL5 chondrites indicates that the L-group is unusually variable and may represent at least 2 sub-groups differing in formation history. Chemical trends in the S/Fe-rich sub-group support textural evidence indicating late loss of a shock-formed Fe-Ni-S melt; the S/Fe-poor sub-group seemingly reflects nebular fractionation only. Highly mobile In and Zn apparently reflect shock-induced loss from L-chondrites. However, contrasting chemical trends in several L-chondrite sample-sets indicate that these meteorites constitute a more irregular sampling of or more heterogeneous parent material than do carbonaceous or enstatite chondrites. Data for L5 chondrites suggest higher formation temperatures and/or degrees of shock than for LL5 chondrites.

INTRODUCTION

In principle, primary nebular condensation and accretion of parent material, secondary metamorphism and melting and tertiary shock-associated processes played roles in determining chondritic mineralogy, petrology and compositions during evolution of parent bodies. In practice, disentangling effects of these events can be difficult, particularly if the secondary and/or tertiary processes, like primary ones, occurred under open-system conditions. The L-group chondrites are illustrative. Although many mineralogic and petrologic characteristics of these and, indeed, all ordinary chondrites indicate substantial metamorphism [cf. Dodd (1969, 1980) and references cited in them], alteration apparently occurred under closed conditions (Ikramuddin et al. 1977; however, see Dodd, 1980). Thus, abundances - even of highly mobile elements - established in L-group chondrites by nebular processes may well have been preserved during secondary events [cf. Binz et al. (1976), Ikramuddin et al. (1977), Takahashi et al. (1978), Bart et al. (1980) and references cited in these papers].

However, properties of L-group chondrites have almost certainly been affected by tertiary impact events. The mineralogy, petrology, noble gas contents and gas-retention ages of many such chondrites exhibit substantial evidence for moderate-to-severe shock-heating resulting from collisional breakup of their parent body or bodies [Anders, 1964; Taylor and Heymann (1971) and references cited therein; Bogard et al. (1976); Smith and Goldstein (1977); Dodd and Jaroswich (1979a)]. Annealing experiments demonstrate that certain elements, i.e. Bi or Tl, are lost more readily than radiogenic ^{40}Ar so that chondrites degassed in massive collisional events should also have lost some proportion of highly-mobile trace elements (Herzog et al. 1979). Indeed, literature data hint strongly at this but are thus far inconclusive because of chondrite heterogeneity.

Invariably, samples for study of trace elements and radiogenic gases bore an unknown relationship to each other and chemical inhomogeneity tends to mask real correlations (Herzog *et al.*, 1979). To complicate matters, major element data hint that the L-group may in fact consist of two or more sub-groups (Dodd, 1976; Dodd and Jarosewich, 1979b). Furthermore, these putative sub-groups may differ in shock history; some LL-group chondrites may also have been severely shocked (Dodd and Jarosewich, 1979a).

We felt that a study of trace elements spanning a range of volatility/mobility and geochemical behavior would shed important light on the origin of L- and LL-group chondrites. In particular, by determining trace elements in aliquots of the same falls used for major element investigations, we could shed light on the existence of L- sub-groups differing in contents of siderophiles and chalcophiles. In addition, such a study might uncover evidence for shock-induced trace element mobilization in both L- and LL-group chondrites although sample selection was not optimum for this purpose. Here, we report results for Ag, As, Au, Bi, Co, Cs, Ga, In, Rb, Sb, Te, Tl and Zn in 14 L- and 3 LL-group chondrites, which have been or are being characterized petrographically and by wet chemical analysis for major elements.

EXPERIMENTAL

Each chondrite studied generally reflected homogenization of 10-20 g of material (two weighed 30 g); hence, each should be representative of the parent chondrite. As prepared, each L- and LL-group chondrite consisted of <100 mesh powdered silicate-plus-finely divided metal and \geq 100 mesh coarse metal fragments. These were mixed in the appropriate proportion by

weight prior to irradiation to obtain a sample as nearly representative of the original chondrite as possible. Allende homogenized reference powder (split 22, position 32) was used to establish experimental precision and accuracy. The first four Allende samples (Table 1) and Apt and AIR (Table 2) were irradiated in the Argonne CP-5 reactor at a fluence of 3×10^{19} neutrons/cm²; all other samples were irradiated in the University of Missouri Research Reactor at a fluence of 2×10^{19} neutrons/cm².

Samples and monitors were prepared, irradiated and treated chemically as described by Ngo and Lipschutz (1980) except for Cs and Rb. These were precipitated as chloroplatinates, redissolved and, after separation of $\text{Cs}_4\text{SiW}_{12}\text{O}_{40}$, Rb_2PtCl_6 was precipitated for counting. The Cs was redissolved and purified, first by precipitation as $\text{Cs}_3\text{Bi}_2\text{I}_9$; then as Cs_2PtCl_6 in which form it was counted. We treated monitors as in Ngo and Lipschutz (1980) except that Rb and Cs, which were in separate vials, were precipitated as PtCl_6^{2-} salts. Average chemical yields for samples were: Ag - 39%; As - 44%; Au - 39%; Bi - 59%; Co - 80%; Cs - 28%; Ga - 42%; In - 29%; Rb - 4%; Sb - 35%; Te - 60%; Tl - 55%; Zn - 44%. Average chemical yields for each monitor element exceeded 80%. Counting and data reduction techniques were as described by Ngo and Lipschutz (1980).

RESULTS

The accuracy and precision of our techniques can be assessed by comparison of our results for homogenized Allende powder (Table 1) with data determined by Bart *et al.* (1980) and Ngo and Lipschutz (1980); these authors had previously compared their data with earlier results and found excellent agreement. For each element, the means of our data and those determined previously fall within 2σ of each other; hence,

the data sets do not differ significantly from each other. The precision of our techniques also seem quite reasonable. Except for As and In where relative uncertainties are 13% and 15%, respectively, precisions do not exceed 8% and, in most cases are 5% or less (Table 1). Hence, our techniques yield reliable data even for Rb where average chemical yields are exceedingly low. Results for samples irradiated in the CP-5 and University of Missouri Research Reactors are indistinguishable (Table 1) despite differences in neutron spectra. Hence, self-shadowing and resonance effects are unimportant for the elements in Table 1 as Ngo and Lipschutz (1980) found for the elements in that study.

Differences should be encountered more frequently when data for homogenized ordinary chondrites and whole-rock chips of the same meteorite are compared, in view of the heterogeneous nature of many chondrites. Unfortunately, few prior results exist for comparison with ours (Table 2); indeed, Te and Tl data are totally lacking. Seven trace elements - As, Au, Co, Ga, Rb, Sb and Zn - exhibit no significant (i.e. more than a factor of two) discrepancies; however, most of these - As, Rb, Sb and Zn - were determined in only one or two of the chondrites we studied. Our Ag and Bi data for Ensisheim are factors of 6 and 42 times higher, respectively, than those of Reed (1963); no other such data exist for meteorites in Table 2. For Cs, our Crumlin datum is 6 times that of Smales et al. (1964) while our Olivenza datum is half of theirs. (Our Cs datum for Bandong looks suspiciously high and we omit it from further consideration: no other Cs data have been reported for this chondrite). Our In datum for Saratov is one-third that of Tandon and Wasson (1967). Since replicate analysis for many of these elements in small, whole-rock samples often differ by as much as an order of magnitude, we believe our results for aliquots of larger homogenized samples to be the more reliable.

DISCUSSION

Elemental concentrations

Trends among non-volatile siderophile elements indicate that the L-group is not as monolithic as supposed hitherto. In addition to clearly delineating the H-, L- and LL-groups, a plot of chondritic S/Mg vs. Fe/Mg atomic ratios demonstrate a greater scatter for the L-group than for the other two (Dodd and Jarosewich, 1979b). On closer inspection of the L-group, systematic differences in S/Fe ratios seem apparent, lending some credence to Dodd's (1976) suggestion of the existence of possible sub-groups. These data place six chondrites in Table 2 - Air, Aumale, Chantonay, Saratov, Tuan Tuc and Vouille - within a possible "S/Fe-rich" sub-group and six others - Apt, Crumlin, Elenovka, Jhung, L'Aigle and Tourinnes-la-Grosse - into a "S/Fe-poor" one. (Both putative sub-groups seemingly occupy their own niches on a S/Mg vs. Fe/Mg plot but may, in fact, be part of a continuum. Whether these chondrites form a continuum or not, significant differences in trace element contents indicate a real variation in the L-group.) Two other chondrites - Ausson and Bald Mountain - are even richer in non-volatile siderophile major elements than those of the putative S/Fe-poor sub-group and we did not include them in it; their inclusion would lead to even more extreme differences between the S/Fe-rich and -poor chondrites and would strengthen our conclusions.

To test possibilities for differences within the L-group population, we determined for each element in each putative sub-group a mean concentration and the associated standard deviation calculated from the dispersion of the individual measurements. We then determined the difference in the means for the hypothesized sub-groups and the standard error of the means for each element.

Means for most elements in Table 2 (i.e. all but Bi, Ga and S) are higher in the S/Fe-poor than in the S/Fe-rich Fe sub-group. However, only three strongly

siderophilic elements - Au, Co and Fe - differ significantly, the differences of the means being 2.8, 2.5 and 2.2 standard errors, respectively. Hence, there is substantial reason to doubt that both chondritic sets are sampling the same parent populations: therefore, two chemical sub-groups are indicated. We consider further properties of these later, in treating interelement relationships.

L-group chondrites in Table 2 can be sorted in other ways and significant group-differences emerge. For example, we tested whether L4 and 5 chondrites differ from L6, irrespective of chemical sub-group or shock history. Practically every element (i.e. all but Bi) has a lower mean concentration in L6 than in the L4 and 5 populations and many differences are statistically significant, the differences in means being 2.1 standard errors for Cs, 2.2 for Co, 2.0 for Fe, 3.6 for In and 3.7 for Zn. Hence, these data suggest that the most petrologically-evolved chondrites are both volatile- and siderophile-poor compared with less-evolved ones. These general trends might have arisen by primary nebular processes (e.g. Blander and Abdel Gawad, 1969; Keays et al., 1971; Wai and Wasson, 1977) but the virtual identity of Fe/Mg, Ni/Mg, S/Mg and Si/Mg mean ratios in L3 and L6 chondrites lacking obvious evidence for shock melting, argues against a primary origin for these differences (Dodd and Jarosewich, 1980b) and against the chemical sub-groups defined by Dodd (1976). Post-accretionary fractionation events may be important for these differences since we grouped together members of at least two different S/Fe populations for these comparisons and have disregarded shock history. L6 chondrites in Table 2 are, on average, more heavily shocked than the L4 and 5 chondrites, the means differing by 3.5 standard errors (with shock facies a - f [Dodd and Jarosewich, 1979a]) being assigned values of 2-7, respectively); however, the difference is only 1.3 standard errors when the entire population of Dodd and Jarosewich (1979a) is considered. If the chondrites are grouped into less- and more-heavily shocked populations - i.e. shock facies a-c and d-f, respectively -

irrespective of Fe content or petrologic grade, contents of most elements decrease with increasing shock (Bi, Ga, Rb and Tl are exceptions). However, only for In are the differences significant, the difference of means being 2.5 standard errors. More heavily-shocked L-chondrites in Table 2 have a somewhat higher petrologic grade, the difference of the means being 2.1 standard errors; this difference is not significant (1.4 standard errors) for the entire population listed by Dodd and Jarosewich (1979a).

Since both S/Fe sub-groups of L-chondrites consist of meteorites of various petrologic grades and shock histories, we cannot unambiguously conclude on the basis of the evidence presented thus far, that chemical compositions of these chondrites reflect mobilization of Fe-Ni-S melts generated by shock-heating (Dodd and Jarosewich, 1979a,b 1980a,b). Where differences are significant - e.g. lower mean contents of non-volatile siderophilic Au, Co or Fe in S/Fe-rich chondrites than in S/Fe-poor ones or mobile In in the more heavily shocked meteorites - they support this idea. However, the decrease in mean contents of Co and Fe or mobile Cs, In and Zn in chondrites of the highest petrologic grade (and shock) could be interpreted in alternative ways. As discussed by Herzog et al. (1979), chondritic petrologic grade and shock intensity can increase with depth within a parent body. Hence, a collateral (possibly even a causal) relation between the two can be expected. This last relation should exist irrespective of whether one assumes that chondritic chemical trends were established by primary, secondary or tertiary processes.

With additional data for only three LL5 chondrites (Table 2), we can add little to current thinking about the genesis of this group. We will merely note that in comparison with L5 chondrites, LL5 chondrites are significantly lower in Fe and Co and higher in Bi, Ga, In and Tl (the differences of the means are 5.8, 3.2, 2.1, 2.2, 2.2 and 2.6 standard errors, respectively). Non-volatile

siderophiles, such as Fe or Co, are well-known to be lower in LL than in L-chondrites; we attribute the higher contents of volatile Bi, Ga, In and Tl in LL chondrites to their having condensed and accreted at somewhat lower temperatures than did L-chondrites (Laul *et al.*, 1973; cf. Binz *et al.*, 1976). Preferential loss of volatiles from L5 chondrites in Table 2 seems unlikely in view of their general slight degree of shock-loading.

Interelement relationships for L-chondrites

Correlation profiles summarize patterns of statistically-significant interelement relationships in a population and often yield important clues to meteoritic genesis (e.g. Biswas *et al.*, 1980); their utility for L-chondrite genesis is limited. We establish these profiles by testing the significance level of linear and exponential (or power curve) relationships between each pair of elements (or physical parameters such as shock history) x and y , i.e. $y = mx + b$ and $y = kx^m$, respectively. Those relationships significant at the 95% confidence level then establish the profile.

The S/Fe-poor sub-group exhibits but 10 pairs of significant relationships (Fig. 1): 5 linear and 7 exponential direct correlations (5 of both kinds) and 3 linear and 1 exponential inverse correlations (1 of both kinds). In contrast, most of the 13 pairs of significant relationships in the S/Fe-rich sub-group (Fig. 1) are inverse correlations - 7 linear and 9 exponential (6 of both kinds); there are but 2 linear and 2 exponential direct correlations (1 of both kinds). For the L-chondrites in Table 2 treated as a single population (Fig. 2), the situation improves slightly: 18 pairs of relationships are significant and, of these, there are 10 linear and 6 exponential direct correlations (6 of both types) and 6 linear and 8 exponential inverse correlations (6 of both types).

The 16 elements and 2 physical parameters (shock and petrologic grade) considered here could yield 153 pairs of significant relationships. Hence, we must

conclude that, compared with carbonaceous (Kurimoto *et al.*, 1973) or L-statite chondrites and achondrites (Binz *et al.*, 1974; Biswas *et al.*, 1980), L-chondrites - no matter what the nominal population - exhibit a very low proportion of significant relationships. This, in turn, re-enforces the conclusion of Binz *et al.* (1976) that L-chondrites (and indeed all ordinary chondrites) constitute a much more irregular sampling of parent matter than do E- or C-chondrites or that parental matter was compositionally more heterogeneous. This conclusion is strengthened by comparing the profile for the 14 L4-6 chondrites in Table 2 with that for the 17 L3-6 chondrites considered by Binz *et al.* (1976). Only three element-pairs correlate in both nominal populations - Fe/Co, As/Co and Bi/Cs - and the first and last of these differ in direction in these two populations (Fig. 2). Clearly, the four populations represented in Figs. 1 and 2 differ markedly.

The profile for the S/Fe-rich sub-group (Fig. 1) suggests fractionation of chalcophiles from siderophiles, probably by shock-induced melting (Dodd and Jaroswich, 1979a,b) rather than by primary nebular processes (Blander and Abdel Gawad, 1969; Keays *et al.*, 1971; Wai and Wasson, 1977). The few siderophile-siderophile direct correlations in this chemical group could reflect this process but it seems more likely that they, and similar covariations in the S/Fe-poor sub-group (Fig. 1) and in the nominal L4-6 population (Fig. 2) reflect nebular processes. Inverse correlations of volatiles, e.g. Zn or In, with shock or petrologic grade (Figs. 2,3) have already been discussed. If, as we suggest, Zn and In were mobilized by shock heating, why do not elements like Bi or Tl (which generally have lower apparent activation energies for loss than Zn or In) correlate inversely with shock? One possibility is that only the most retentively-sited fractions of highly-labile Bi or Tl remain after shock-induced loss so that statistically significant trends cannot be expected. Alternatively, shock-induced Bi or Tl losses may have been less extensive than were variations in primary

contents. These ad hoc explanations are not satisfying but no better choices are available in the absence of additional data.

A major difficulty in interpreting correlation profiles for L-chondrites is that some interelement trends in chemical sub-groups are mutually re-enforcing; others tend to have no mutual effect while still others are self-cancelling. To illustrate these, we list in Table 3 significance levels of selected pairs of elements/properties for members of each chemical sub-group and in the nominal population defined by the 14 L4-6 chondrites in Table 2. We included all pairs for which L-chondrites in Table 2 yield at least two correlations significant at >95% confidence level in one or more populations (Figs. 1,2); this should minimize the number of chance correlations considered.

The In/shock inverse correlations (like those of In or Zn/petrologic grade or Zn/shock or the In/Zn or As/Au direct correlations, e.g. Table 3) illustrate a re-enforcing case (Fig. 3). The correlation for the nominal L4-6 population is significant at >99% confidence level, a level higher than those of either constituent sub-group (Table 3). It is not necessary that the correlation in each sub-group have the same sign for re-enforcing to occur. For example, Fe and Co correlate directly in the S/Fe-poor sub-group (as they typically do in other chondrite groups) but inversely in the S/Fe-rich sub-group, presumably due to Fe removal (Fig. 4). In each sub-group, the significance levels are 94-98%, and in the nominal L4-6 population the significance levels exceed 99.9% (Table 3, cf. Fig. 4). Normally, one would expect correlations of opposite sign in separate populations to interfere when these groups are treated as a nominal single population; the Co/S pair illustrates this best (Fig. 5). Here, a strongly positive correlation in the S/Fe-poor sub-group and a strongly negative one in the S/Fe-rich case yield an essentially randomized array when combined (cf. Table 3). Other correlations in Table 3 fall into one of these categories.

In view of the importance of Bi, In and Tl as indicators of thermal processes (cf. Laul *et al.*, 1973; Binz *et al.*, 1974, 1976; Ikramuddin *et al.*, 1977; Herzog *et al.*, 1979; Biswas *et al.*, 1980), we illustrate in Fig. 6 two-element trends involving these in the L- and LL-chondrites in Table 2. We also illustrate theoretical condensation curves for the two-component model of Anders and co-workers (e.g. Laul *et al.*, 1973); we "adjusted" our empirical Bi, In and Tl data with Ga to accord with requirements of the model. As can be seen, the general agreement of the data with the theoretical condensation curves seems quite satisfactory. Unfortunately, we cannot eliminate the possibility that the trends might reflect partial loss of mobile elements by shock-heating (Dodd and Jarosewich 1979a,b, 1980a,b; Herzog *et al.*, 1979) in view of elemental mobilities of Bi, In and Tl established in simulated metamorphic experiments (Ikramuddin *et al.*, 1977). Clearly, additional experiments are required to establish the response of those elements to shock heating: these are in progress.

CONCLUSIONS

While compositional trends in L-group chondrites are not totally clear-cut with regard to fractionation processes, trace and major element data and petrologic information yield some important genetic information. These chondrites constitute a much more irregular sampling of or more heterogeneous parent material than do enstatite or carbonaceous chondrites and L-chondrites constitute at least two chemical sub-groups, possibly a considerable continuum. The S/Fe-rich sub-group exhibits compositional and textural evidence for late loss of a shock-formed Fe-Ni-S melt and accompanying trace elements while compositionally, the S/Fe-poor sub-group apparently reflects only primary fractionation processes. Contents of some highly-mobile trace elements, e.g. In or Zn, indicate shock-induced vaporization and loss but other such elements, e.g. Bi or Tl, seem pre-

dominantly to reflect condensation processes; late tertiary loss could have modified initial Bi and Tl contents, however. The L6 chondrites analyzed to date contain, on average, lesser amounts of volatile/mobile elements: whether these trends reflect primary or tertiary loss is an open question. Compositional trends in the few LL5 chondrites we studied are consistent with prior data indicating lower siderophile and higher volatile element contents than in L5 chondrites, hence lower formation temperatures and/or lesser degrees of shock. Since trends for many elements in L-chondrites are ambiguous and could indicate fractionation by either primary or tertiary processes, additional experiments seem warranted to delineate effects of extensive shock upon meteoritic compositions.

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Table 1. Trace element contents of Allende homogenized powder replicates.

Sample	Ag (ppb)	As (ppm)	Au (ppb)	Bi (ppb)	Co (ppm)	Cs (ppb)	Ga (ppm)	In (ppb)	Rb (ppb)	Sb (ppb)	Te (ppm)	Tl (ppb)	Zn (ppm)
1*	97.8	1.51	170	51.1	597	80.8	6.24	-	1170	92.3	1.13	61.4	118
2*	105	1.76	147	-	606	78.5	6.15	-	887	106	1.10	62.7	119
3*	104	1.21	142	-	606	87.2	6.07	25.6	835	108	1.11	61.7	119
4*	95.2	1.39	138	-	640	87.3	6.28	28.8	912	106	1.08	65.9	122
5†	95.7	1.35	142	-	650	83.1	5.80	35.2	973	98.8	1.10	61.6	115
6†	105	1.59	158	49.4	599	81.8	6.28	26.8	1190	100	1.02	62.9	113
Mean§	100±	1.47±	149±	50.2±	616±	83.1±	6.14±	29.1±	980±	102±	1.09±	62.7±	118±
5	0.19	12	1.2	23	3.5	0.18	4.3	13	6	0.04	1.7	3	
94.9±	1.44±	142ξ	50.6¶	619±	89.8±	6.73±	33.9±	1110±	75±	1.02±	59.5±	120±	
7.2¶	0.22ξ	-	-	13¶	5.0¶	0.76¶	3.2¶	50ξ	11ξ	0.02¶	3.9¶	6¶	
101±	49.0±	49.0±	612±	89.3±	6.27±	35.6±	35.6±	1.09±	59.6±	115±			
4ξ	0.7ξ	10ξ	3.3ξ	0.30ξ	1.0ξ	0.13ξ	2.2ξ						

Notes and References to Table 1.

- * Samples irradiated in the CP-5 Reactor.
- † Samples irradiated in the University of Missouri Research Reactor.
- § Uncertainties are one estimated standard deviation from the mean calculated from the dispersion of the individual measurements.
- ¶ Bart et al. (1980)
- ¤ Ngo and Lipschutz (1980)

Table 2. Shock exposure and compositional information on 14 L- and 3 LL-chondrite falls.

Major elements^a:Trace elements^a:

Chondrite and classification ^b	Shock facies	Fe	Ni	S	Ag	As	Au	Bi	Co	Cs	Ga	In	Rb	Sb	Te	Tl	Zn
		%	%	%	ppb	ppm	ppb	ppb	ppm	ppb	ppm	ppb	ppb	ppb	ppb	ppm	
Bald Mountain (L4)	d	23.52	1.26	-	62.2	1.4	190	4.93	610	64.2	4.53	1.1	2.32	89	376	9.03	-
Saratov (L4)	c	21.73	1.16	2.04	52.5	1.2	160	7.49	545	34.3	5.03	2.6	2.27	300	442	1.70	68.0
Ausson (L5)	b	23.77	1.33	2.09	93.7	1.9	190	13.4	636	16.1	5.56	1.6	2.25	2300	521	3.02	54.3
Crumlin (L5)	c	21.56	1.09	1.72	47.9	1.0	170	4.48	504	34.5	5.07	-	2.19	180	405	0.83	47.6
Elenovka (L5)	a	23.04	1.24	2.29	62.7	1.5	180	8.22	581	20.5	-	3.1	1.61	82	-	5.09	75.8
Jhung (L5)	b	22.00	1.28	1.89	264	1.4	170	10.2	545	2.43	-	1.2	1.01	81	315	7.49	64.8
Air (L6)	d	21.78	1.41	2.36	72.6	1.2	180	6.74	625	11.9	5.59	-	-	-	-	1.68	70.2
Apt (L6)	d	21.58	1.34	1.69	96.4	1.4	220	-	561	9.12	4.38	0.50	0.58	83	348	3.05	58.1
Aumale (L6)	d	21.65	1.26	2.12	114	1.0	120	5.88	520	8.77	5.14	0.80	1.77	120	378	1.50	41.3
Chantonnay (L6)	f	21.13	1.17	1.93	60.5	1.4	150	9.03	526	28.4	5.36	0.40 [±]	1.73	66	394	1.31	42.4
L'Aigle (L6)	d	22.79	1.29	2.40	74.6	0.8	110	8.69	602	-	5.14	<0.6	2.28	75	444	0.40	41.6
Tourinnes-la-Grosse (L6)	c	21.98	1.16	1.82	60.6	1.4	220	-	530	5.62	3.64	0.50 [±]	1.77	840	315	2.03	47.0
Tuan Tuc (L6)	e	21.53	0.78	1.76	82.4	1.3	160	6.70	559	6.43	5.87	<0.2	1.56	100	254	5.25	41.1
Vouillé (L6)	e	21.52	1.12	2.52	136	0.9	130	21.5	491	3.10	4.89	<0.70	2.25	300	401	4.25	45.9
Olivenza (LL5)	-	18.50	-	-	71.7	0.8	120	10.1	407	26.4	5.59	14.3	1.73	59	254	7.99	57.1
Bandong (LL5)	-	19.60	-	2.19	99.2	1.6	160	38.2	422	3070	5.81	5.7	1.80	76	446	26.6	59.0
Ensisheim (LL5)	-	19.22	-	-	192	1.3	190	32.7	522	19.1	6.42	26.5	0.26	64	112	31.5	53.1

Notes to Table 2.

* Data in italics indicate cases where Rb contents seems acceptable despite low chemical yields. The two omitted Ga data also involved low chemical yields but seemed unreasonably high. Other omissions involve cases where data were not determined.

† Data in weight percent. Dodd and Jarosewich (1980a,b) reported some of these data earlier.

§ Nearly all samples studied were obtained from the Paris Museum. The exceptions are: Bald Mt. and Saratov - Field Museum of Natural History; Crumlin and Jhung - British Museum (Natural History); Elenovka - Committee on Meteorites (U.S.S.R.); Bandong - U.S. National Museum.

Table 3. Significance levels for relationships involving elements, shock and/or petrologic grade in normal and depleted sub-groups and L chondrites treated as a single population.

Pair*	Normal*		Depleted*		L-group*	
	lin.	exp.	lin.	exp.	lin.	exp.
As/Au	+97	+98	+88	+88	+99	+99
Ag/Au	0	+ 4	-97	-97	- 3	-27
S /Au	-89	-89	-68	-64	-96	-97
Fe/Co	+98	+98	-94	-95	+99.9	+99.9
Ga/Co	+71	+68	+98	+98	+88	+86
S /Co	+96	+96	-97	-97	- 2	- 8
Ga/Ni	+62	+60	-96	-95	-45	-47
Te/Ni	+36	+34	+77	+89	+96	+98
S /Fe	+99.9	+99.9	+70	+72	+77	+79
S /As	-51	-52	-96	-96	-69	-70
Te/Sb	-76	-66	+69	+57	+99	+97
S /Ga	+49	+45	-97	-97	- 9	- 2
PG/Cs	-64	-73	-88	-78	-99	-99
Bi/S	+68	+76	+93	+92	+98	+99
Tl/Zn	+96	+97	-41	-28	+76	+79
In/Zn	+93	+98	+99	+93	+99.9	+99.9
SH/Zn	-93	-93	-90	-93	-99	-99.9
PG/Zn	-75	-74	-99	-98	-99	-99
SH/In	-97	-98	-92	-92	-99	-99
PG/In	-89	-94	-99.9	-92	-99	-99

Notes to Table 3.

* Relationships significant at $\geq 95\%$ confidence level are listed in regular type; significance levels below this value are indicated in italics. Positive and negative signs indicate direct and anti-correlations, respectively. The terms lin. and exp. refer to linear/linear and logarithmic/logarithmic relationships, respectively.

[†] Notations SH and PG indicate shock classification and petrologic grade, respectively.

FIGURE CAPTIONS

Fig. 1. Correlation profiles for statistically-significant (>95% confidence level) interelement relationships in S/Fe-poor and -rich sub-groups of L-chondrites (regions right and left of diagonal, respectively). Elements are listed from left to right and top to bottom in order of presumed volatility during nebular condensation (Grossman and Larimer, 1974; Wai and Wasson, 1977; Takahashi *et al.*, 1978). Shock (SH) and petrologic grade (PG) have been entered last as these physical parameters should be associated with thermal processes. Linear/linear and logarithmic/logarithmic direct correlations are represented by circles and crosses, respectively; analogous inverse correlations are represented by diamonds and plus signs, respectively. The profiles for the two sub-groups differ markedly. Of the few relationships that are significant, most in the S/Fe-rich sub-group are inverse while most in the S/Fe-poor sub-group are direct. Relationships significant in one sub-group are not necessarily duplicated in the other. These point to differences in fractionation processes for the two sub-groups (see text).

Fig. 2. Correlation profiles for 14 L4-6 chondrites reported here and for 17 L3-6 chondrites discussed by Binz *et al.* (1976) - regions right and left of diagonal, respectively. Symbols are as in Fig. 1. Although significant relationships are more abundant in these nominal populations than in the S/Fe-poor or -rich sub-groups, their absolute proportions are still quite low. There is virtually no overlap in the profiles of the two nominal populations, suggesting that L-chondrites constitute an irregular sampling of or compositionally heterogeneous parent material. However, both profiles hint that primary overall fractionations involved covariation of siderophiles and loss of very mobile elements during late shock (see text).

Fig. 3. Correlations of In with shock in S/Fe-poor and -rich L-chondrites and Ausson and Bald Mt.. Diamonds, stars and hexagons denote L4, L5 and L6 chondrites, respectively. Indium loss with increasing shock may be causal and/or collateral. Trends of other elements indicate the former as more likely (see text).

Fig. 4. Correlations of Co with Fe in L4-6 chondrites (symbols are as in Fig. 3). These elements correlate inversely in the S/Fe-rich case and directly in the S/Fe-poor one; by combining the two populations, a stronger direct correlation results. (See text and contrast with Fig. 5).

Fig. 5. Correlations of Co with S in L4-6 chondrites (symbols as in Fig. 3). As with the Co/Fe case, the S/Fe-rich and -poor sub-groups correlate strongly in inverse and direct fashions, respectively. However, a random array results when the populations are combined (cf. Fig. 4). Trends such as these complicate interpretation of correlation profiles.

Fig. 6. Two-element correlation diagrams involving Bi, In and Tl in L- and LL-chondrites compared with theoretical condensation curves at nebular pressures of 5×10^{-4} , 10^{-5} and 5×10^{-5} atm. Squares, stars and hexagons denote chondrites of petrologic types 4, 5 and 6, respectively. Abbreviations: Apt (AP); Aumale (AUM); Ausson (AU); Bald Mt. (BM); Bandong (BD); Chantonay (CH); Crumlin (R); Elenovka (EL); Ensisheim (EN); Jhung (JH); L'Aigle (LA); Olivenza (OL); Saratov (SA); Tourinnes-la-Grosse (TLG); Tuan Tuc (TT); Vouille (VO). The experimental data are consistent with theoretical condensation curves but could be interpreted as reflecting some loss after late shock-heating (see text).

AU CO NI FE RB AS SB AG GA CS S TE ZN BI TL IN SHPG

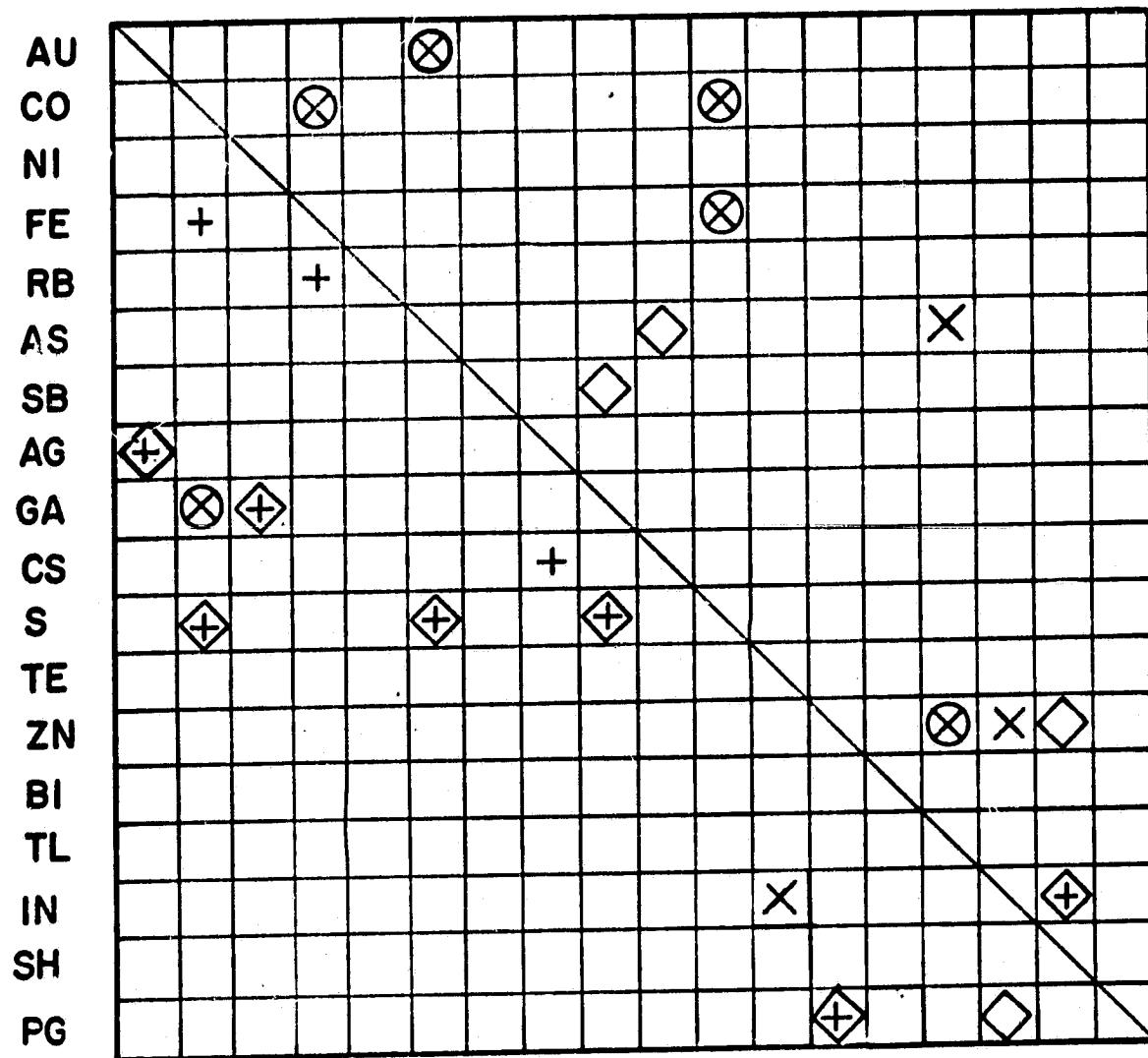


Fig. 1

AU CO NI FE RB AS SB AG GA CS S TE ZN BI TL IN SH PG

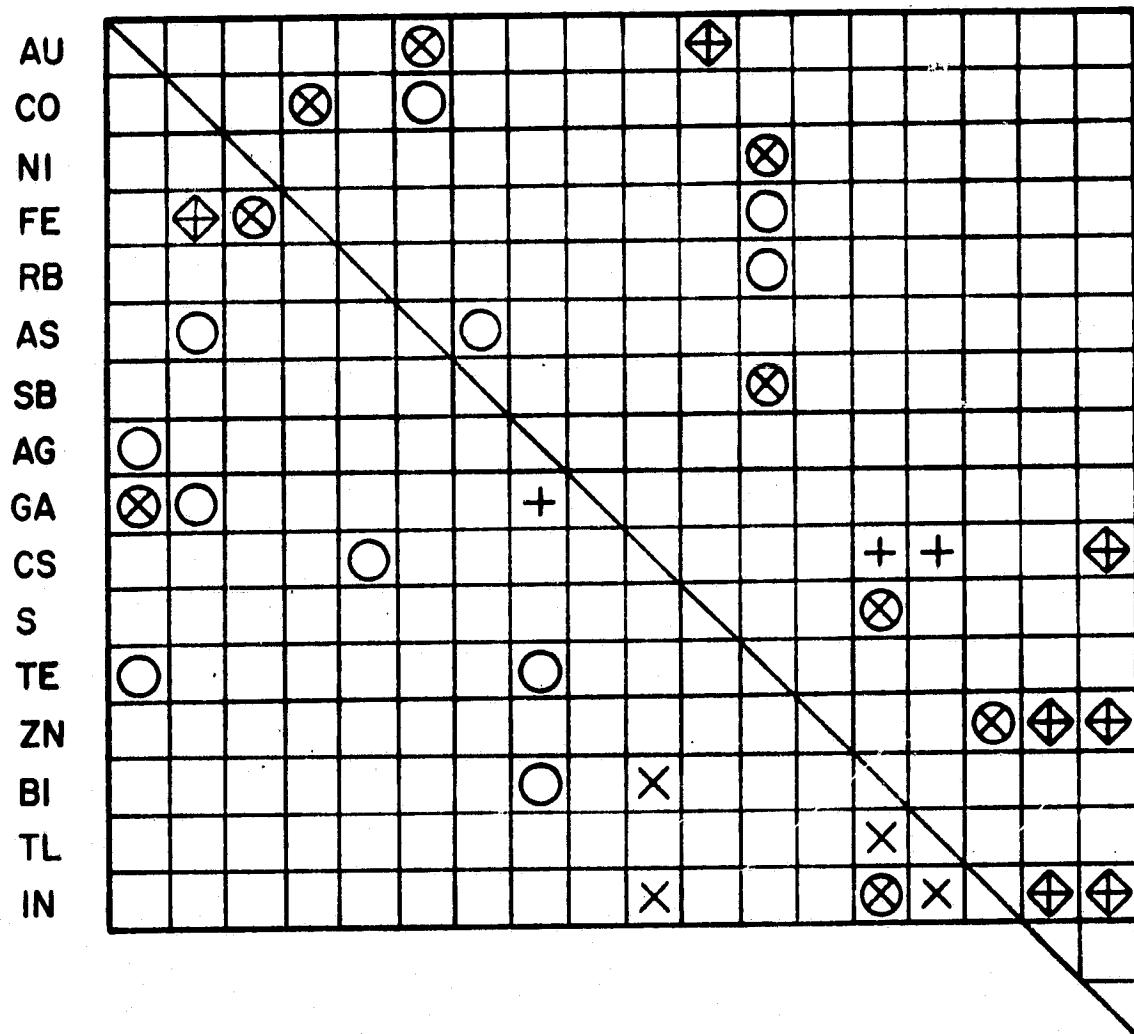
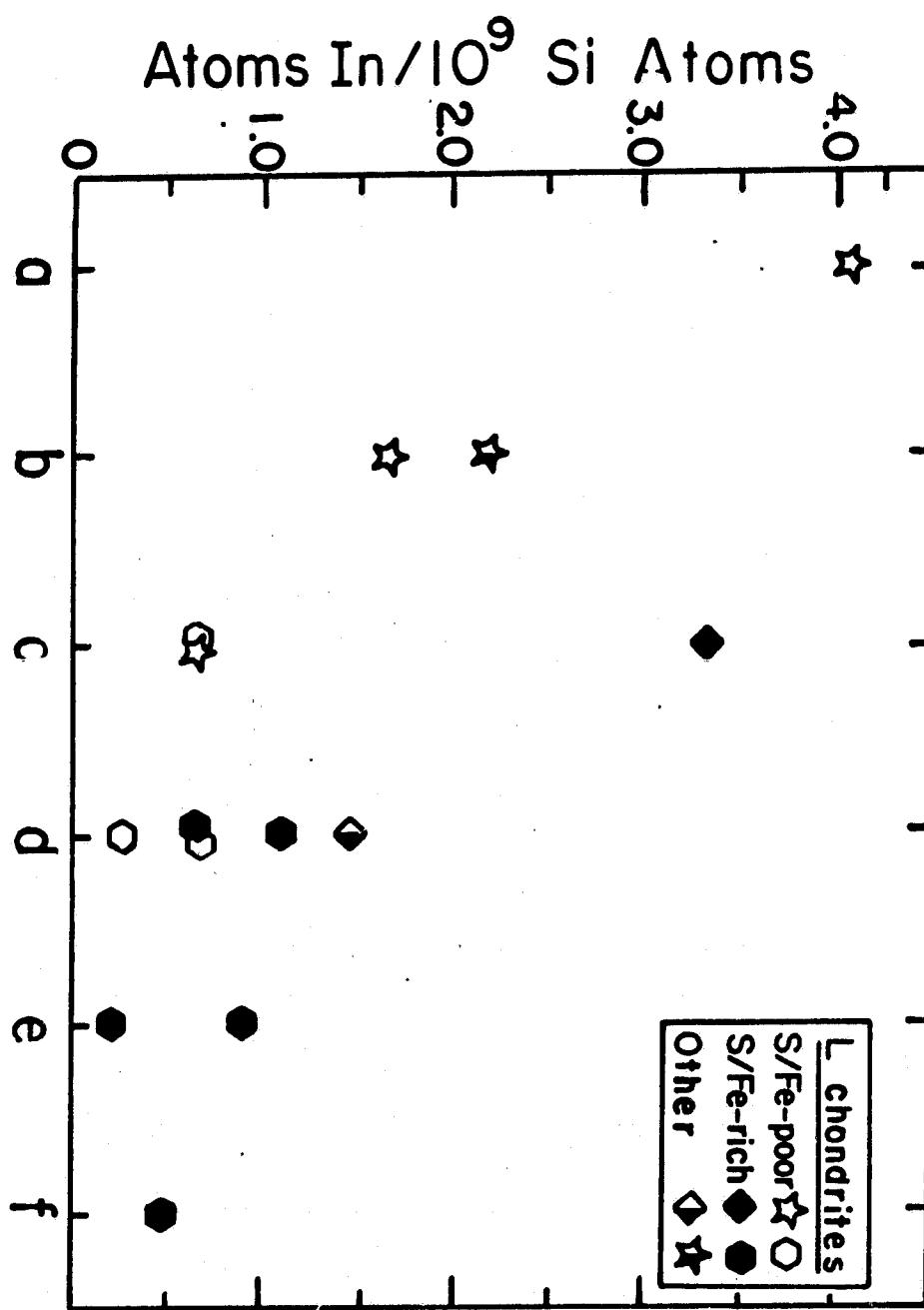


Fig. 2

Shock Classification



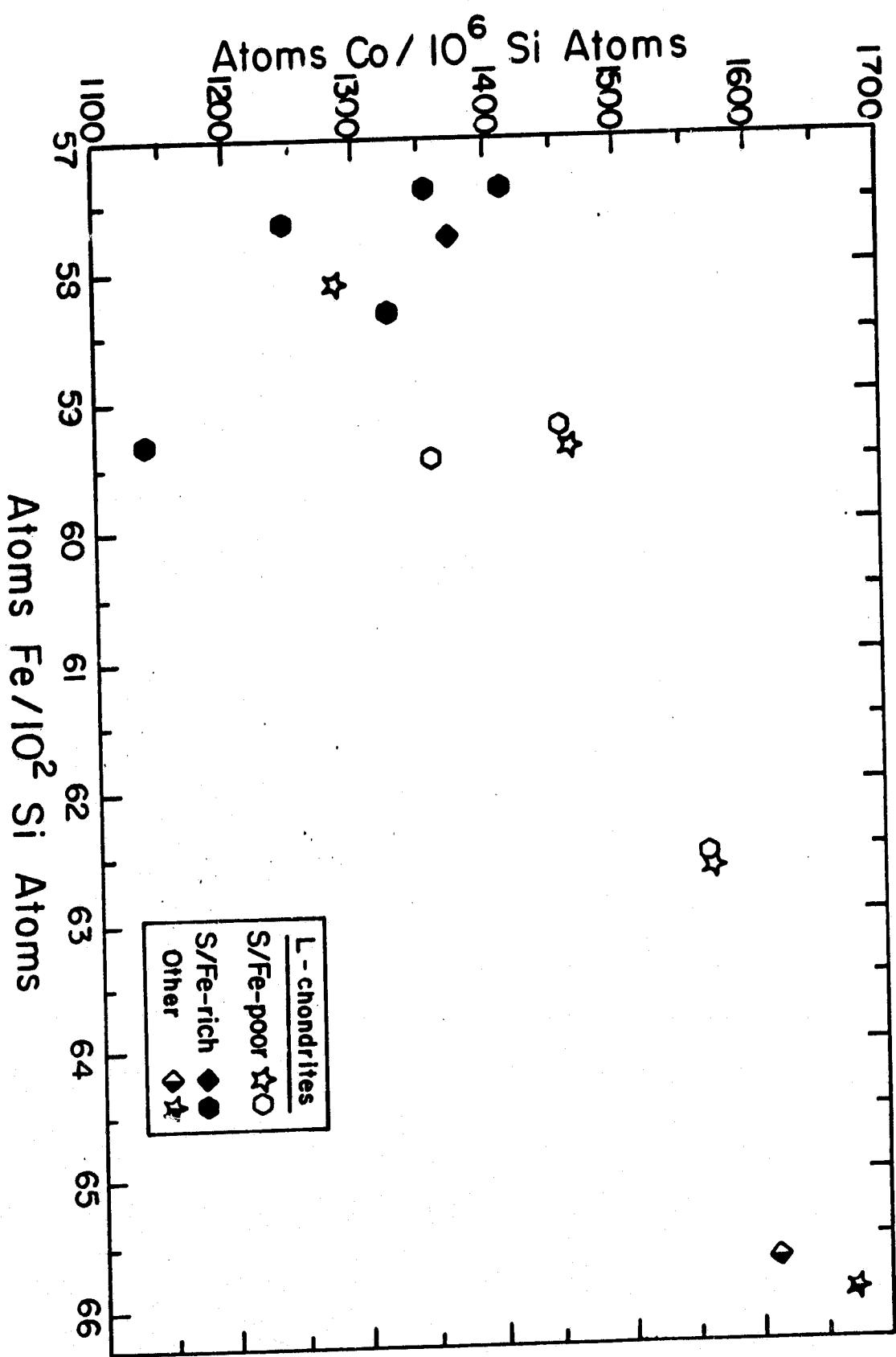


Fig. 7

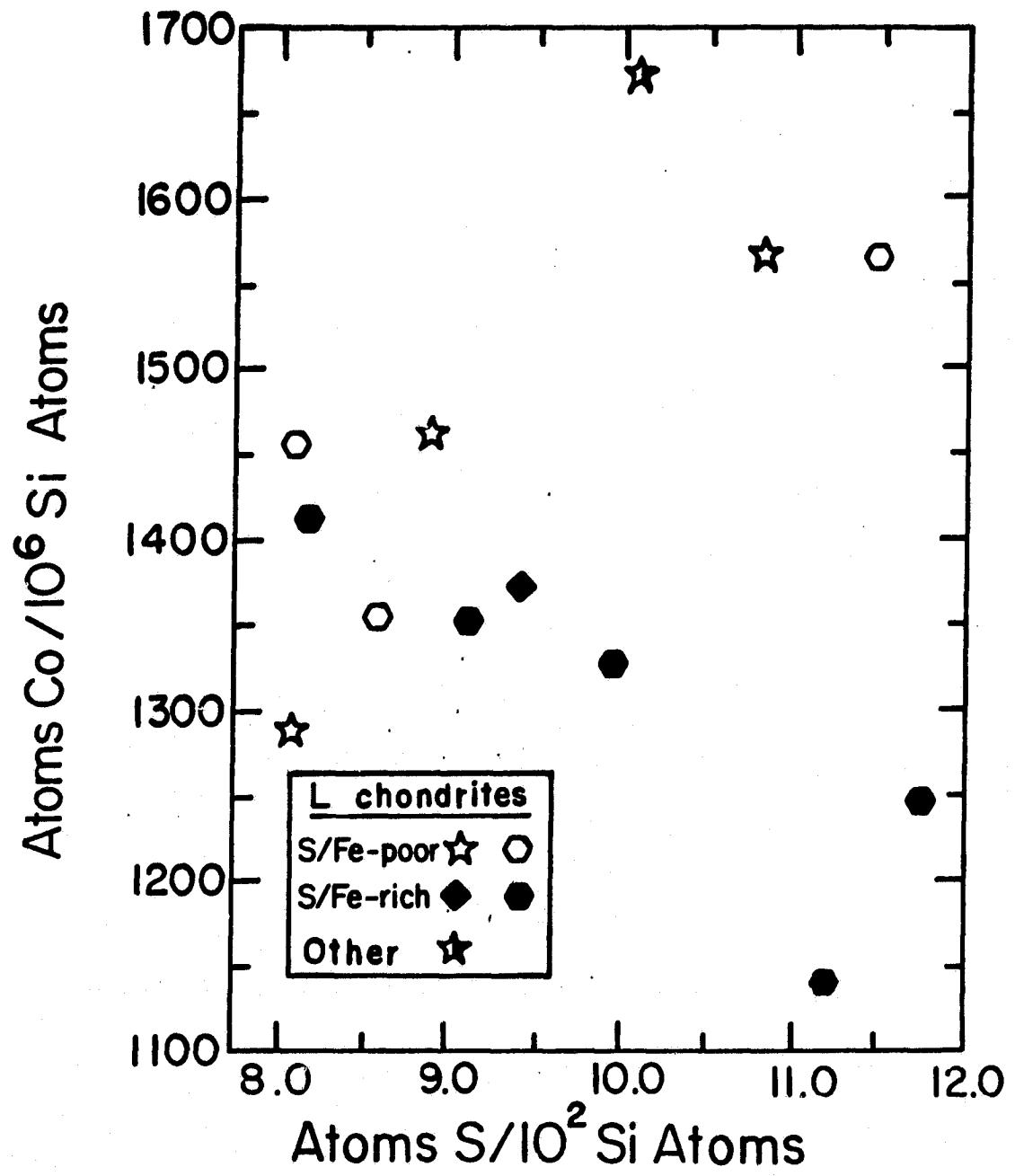


Fig. 5

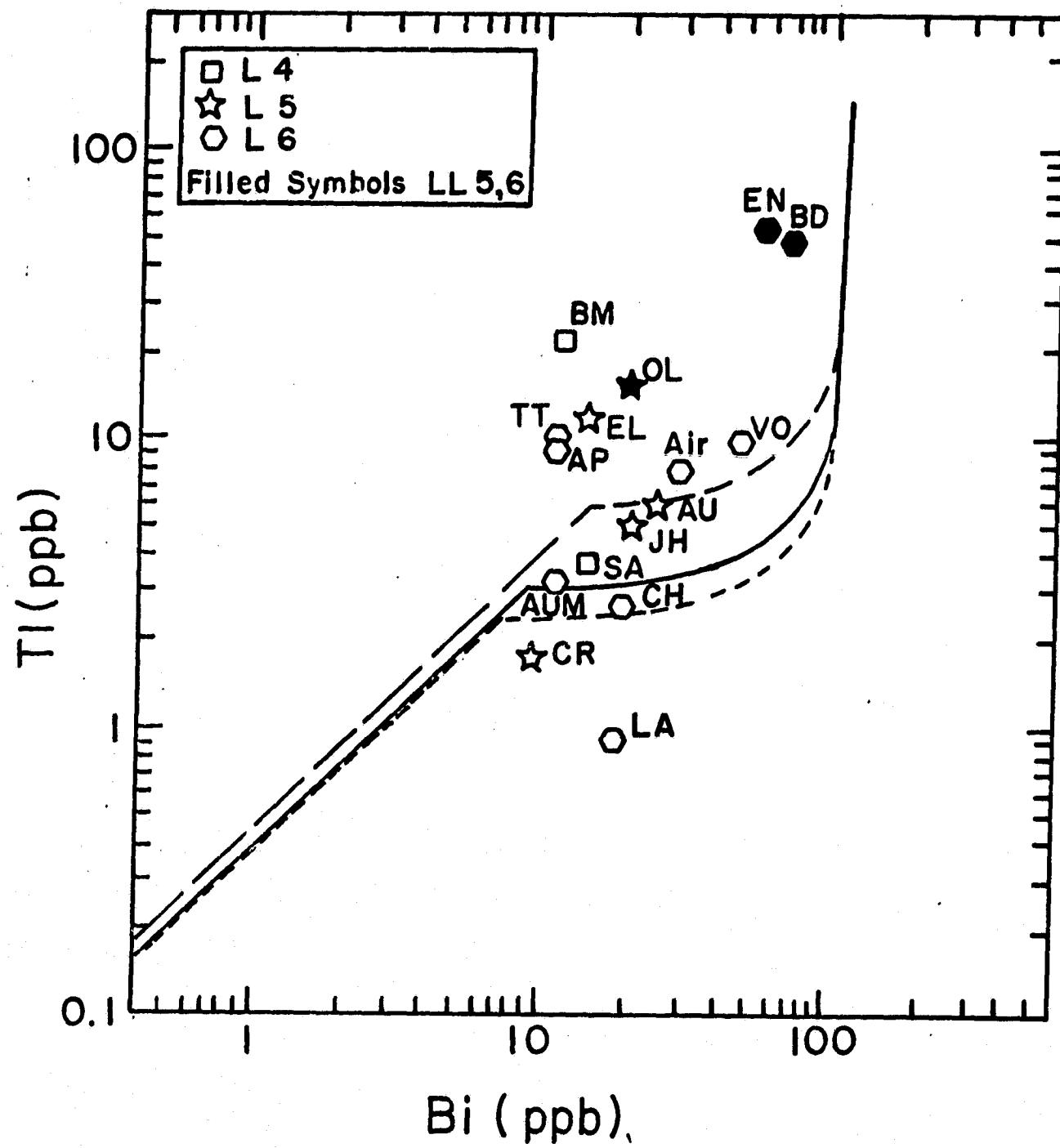


Fig. 6a

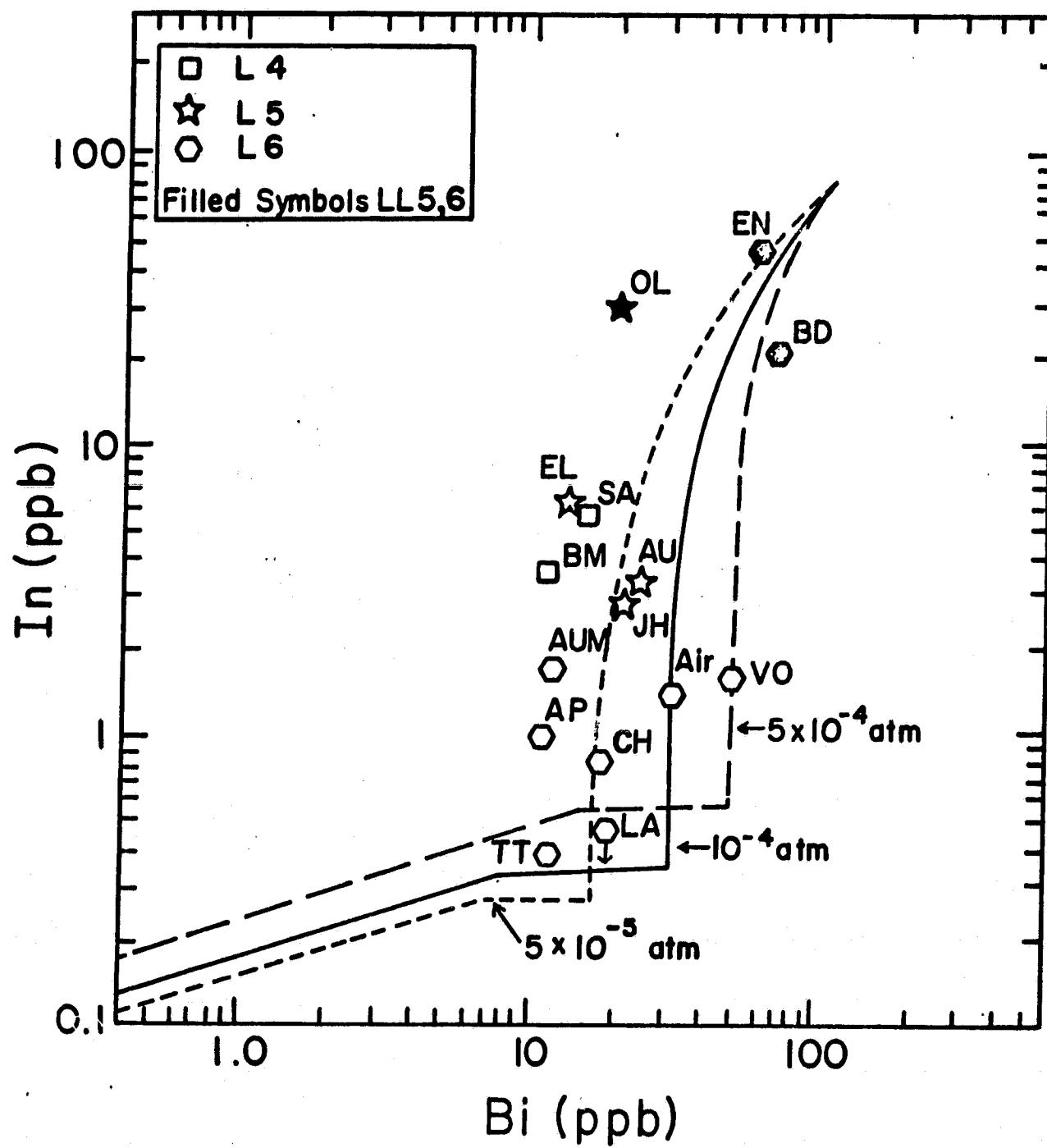


Fig. 6b

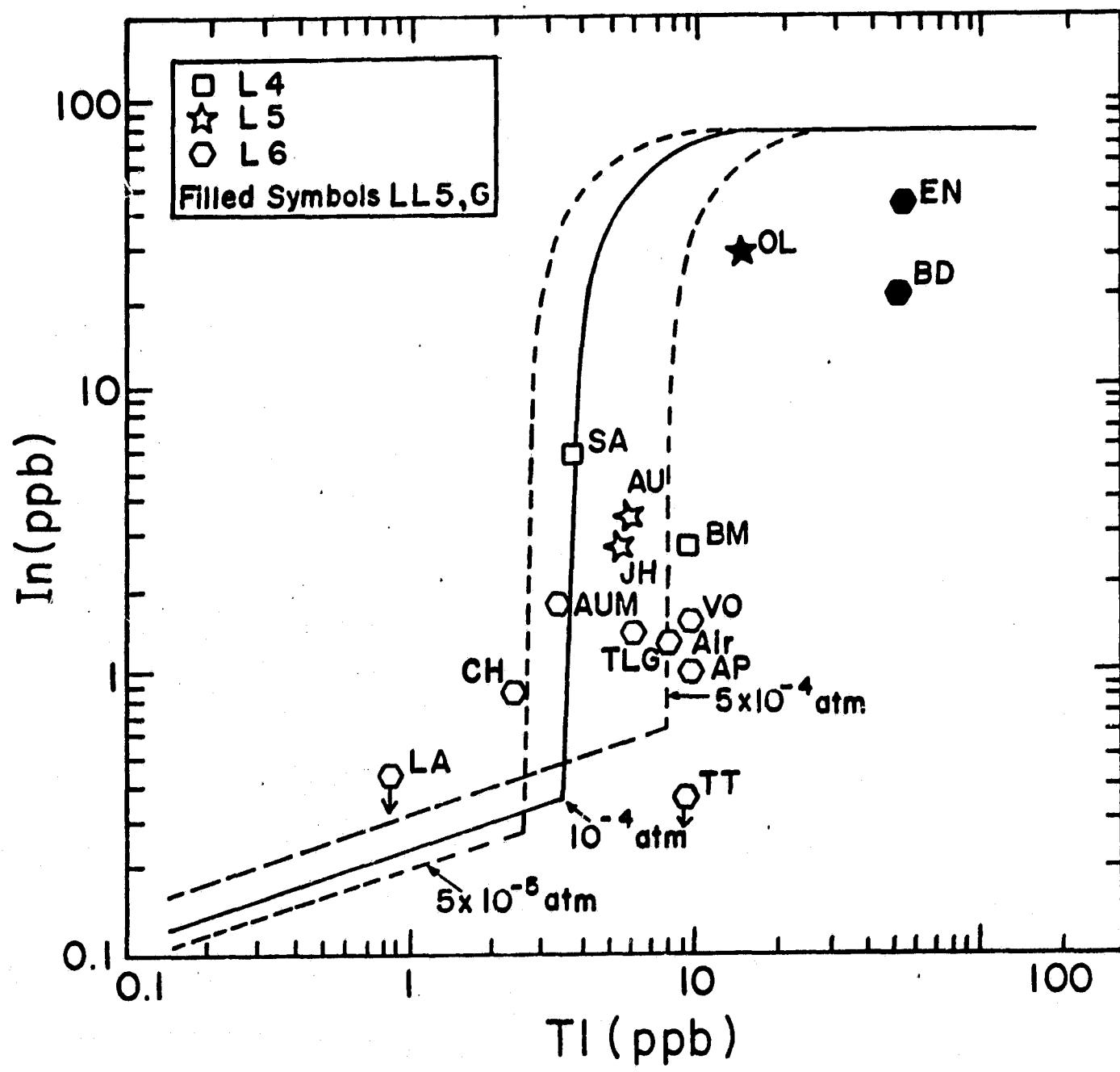


Fig. 6c